AFRL-RH-WP-TR-2008-0082

Toolkit for Tactical Visualizations that Represent Uncertainty Dynamically

Xinyu Zhang
Celestine A. Ntuen

College of Enginering and Dept. of Industrial and Systems Engineering
North Carolina A&T State University
1601 E. Market St.
Greenboro NC 27411-0001

April 2008

Final Report for the period August 2006 to May 2008

Air Force Research Laboratory
Human Effectiveness Directorate
Warfighter Interface Division
Battlespace Visualization Branch
Wright-Patterson AFB OH 45433

NOTICE AND SIGNATURE PAGE

THIS TECHNICAL REPORT HAS BEEN REVIEWED AND IS APPROVED FOR PUBLICATION.

AFRL-RH-WP-TR-2008-0082

FOR THE DIRECTOR

//signed//
Daniel Repperger
Program Manager
Battlespace Visualization Branch

//signed//
DANIEL G. GODDARD
Chief, Warfighter Interface Division
Air Force Research Laboratory

REPORT DOCUMENTATION PAGE

Form Approved
OMB No. 0704-0188

1. REPORT DATE *(DD-MM-YYYY)*
21 Apr 2008

2. REPORT TYPE
Final

3. DATES COVERED *(From - To)*
August 2006 – May 2008

4. TITLE AND SUBTITLE
Toolkit for Tactical Visualizations that Represent Uncertainty Dynamically

5a. CONTRACT NUMBER
FA8650-06-1-6744

5b. GRANT NUMBER

5c. PROGRAM ELEMENT NUMBER
62202F

6. AUTHOR(S)
Xinyu Zhang
Celestine A. Ntuen

5d. PROJECT NUMBER
7184

5e. TASK NUMBER
11

5f. WORK UNIT NUMBER
NC

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)
College of Engineering and Dept. of Industrial and Systems Engineering
North Carolina A&T State University
1601 E. Market St.
Greensboro NC 27411-0001

8. PERFORMING ORGANIZATION REPORT NUMBER

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)
Air Force Materiel Command
Air Force Research Laboratory
Human Effectiveness Directorate
Warfighter Interface Division
Battlespace Visualization Branch
Wright Patterson AFB OH 45433-7022

10. SPONSOR/MONITOR'S ACRONYM(S)
AFRL/RHCV

11. SPONSORING/MONITORING AGENCY REPORT NUMBER
AFRL-RH-WP-TR-2008-0082

12. DISTRIBUTION AVAILABILITY STATEMENT
Approved for public release; distribution is unlimited.

13. SUPPLEMENTARY NOTES
AFRL/PA Cleared 6/11/2008 WPAFB 08-3637.

14. ABSTRACT
Decisions are usually made under uncertainty, so displaying uncertainty information is very important to decision-making. In the past, uncertainty information associated with tactical symbols was ignored. Recent research explored uncertainty display techniques and investigated the capabilities of the human perceptual system. However, most previous studies focused on static display, and limited techniques. In this report, we investigated dynamic display of uncertainty information of tactical symbols. A comparison study was carried out for three display methods: rectangular bar, color saturation, and blurred image. This report reviews uncertainty display methods, describes the design and development of the software toolkit, and discusses the experimental procedure and results. A new method for dynamic display of uncertainty, an automatic feature based morphing, was also developed and included in the report.

15. SUBJECT TERMS
Dynamic, Morphing, Symbology, uncertainty, visualization, FY06 HBCU/MI

16. SECURITY CLASSIFICATION OF: Unclassified			17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON
a. REPORT	b. ABSTRACT	c. THIS PAGE			George Reis
U	U	U	SAR	47	19b. TELEPONE NUMBER (*Include area code*)

Standard Form 298 (Rev. 8-98)
Prescribed by ANSI-Std Z39-18

This page blank intentionally.

Table of Contents

List of Figures

List of Tables

THIS PAGE INTENTIONALLY LEFT BLANK

1. Summary

Computer-generated display is widely used these days and decision-making relies on both accurate information and efficient visualization techniques. Tactical symbols are often used in the display of battlefield information. In the past, uncertainty information associated with tactical symbols was ignored. Recent research explored uncertainty display techniques and investigated the capabilities of the human perceptual system. However, due to the lack of an efficient tool, previous work focused only on the static display, and limited techniques have been studied. The purpose of this project is to develop a software toolkit, which displays tactical symbols dynamically, and to use it to understand the influence of visualization techniques on human decision-making. This report describes the design and development of the software toolkit, the experimental procedure and results, and the development of a new method for dynamic display of uncertainty – an automatic feature based morphing. Section 2 is an introduction of this project. Section 3 provides a literature review of graphical display of uncertainty and previous human factors study on uncertainty representations. Section 4 describes the functionality of the software toolkit and its development. Section 5 discusses the findings from the experiment conducted using the developed toolkit. Three uncertainty display techniques (rectangular bar, color saturation and blurred image) have been compared and the results support our hypothesis. A feature based morphing algorithm is developed and implemented in the toolkit for future investigation of its capability of display of uncertainty for tactical symbols. Section 6 explains the algorithm. Finally, we draw conclusions in Section 7.

2. Introduction

The uncertainty associated with tactical symbols seems limitless. There are various uncertainty definitions and there is no real consensus. Here we refer uncertainty to a lack of sureness or definite knowledge about an outcome result (Andre & Cutler, 1998). Uncertainty information can be provided in a frequency format or a probability format, which can be given in linguistic, numerical, or graphical representation. In our study, we focus on the graphical display and situations which require decisions to be made in a timely manner. A software toolkit was developed to assist this study.

2.1. Tactical Symbols

A wide range of symbolic representations are used in information visualization, such as Chernoff faces and multidimensional icons (Spence, 2001). In the military, to ensure the compatibility and the interoperability of DoD Command, Control, Communications, Computer and Intelligence system development, MIL-STD-2525B (DoD, 1999) was published. MIL-STD-2525B is the current standard for war fighting symbology. The MIL-STD-2525B defines two categories of warfighting symbology: tactical symbols and tactical graphics. Tactical symbols are point objects that present information that can be pinpointed in one location at a particular point in time. A tactical symbol is composed of a frame, fill, and icon. At the same time, it may include text and/or graphic modifiers that provide additional information.

- The frame is the geometric border of a symbol, which provides an indication of the affiliation, battle dimension, and status of a warfighting object.
- The fill is the interior area within a symbol. If a color fill is used in a framed symbol, it provides redundant information about the affiliation of the object.
- The icon is the innermost part of a symbol, which provides an abstract pictorial or alphanumeric representation of a warfighting object. The icon portrays the role or mission performed by the object.
- A modifier provides optional additional information about a symbol.

We use the fixed wing aircraft symbols in our experiment. The friendly and hostile symbols are shown in Figure 2-1. Different symbols can also be used in the toolkit with their image saved in portable network format (PNG) formats.

Figure 2-1. Friendly and hostile symbols used in the experiment.

2.2. Technical Approaches

This study consists of several tasks. The goal and approach of each task are explained below.

a) Literature review. The goal of this task is to review the display methods that are suitable for dynamical uncertainty display of tactical symbols and to select the methods for the comparison experiment. This review was conducted by reviewing papers and reports in uncertainty visualization in broad fields and human factors study on uncertainty representation.

b) Design of experiment. The goal is to design the experiment to compare selected display methods. Scenarios were created to simulate real-life situations and to provide contexts of spatial and state problems.

c) Development of a software toolkit. The goal of this task is to provide a tool for conducting the experiment. A software toolkit was developed to display tactical symbols in designed scenarios with selected display methods and to collect experimental data.

d) Conducting the experiment and analyzing experiment results. The goal of this task is to find out if there are differences between the selected methods on perception of uncertainty and decision making. The subjects were recruited from students in the college of engineering at North Carolina A&T State University. Data were collected using the developed toolkit and analyzed with statistics software.

e) Exploring new methods for uncertainty display. The goal is to provide a method to display uncertainty by shapes. A morphing algorithm was developed and implemented in the software toolkit.

3. Literature Review

In this literature review, information is collected to allow designers to determine what issues are important when designing the visualization tool for military applications, to select methods for display and visualization, and to understand how humans detect uncertainty changes. Section 3.1 reviews uncertainty visualization techniques. Section 3.2 provides a review on dynamic display techniques. Section 3.3 discusses previous studies on the impact of uncertainty visualization techniques on decision making. Section 3.4 lists existing toolkits.

3.1. Uncertainty Visualization

Uncertainty information can be provided in a frequency format or a probability format, which can be given in linguistic, numerical, or graphical representation. Kirschebaum and Arruda (1994) studied effects of graphic and verbal probability information on command decision making within a context of a spatial problem. Their results suggest a graphic representation of uncertainty may considerably improve the judgments of decision makers. Bisantz, Marsiglio, and Much (2005) investigated different uncertainty representation formats' influence on decisions of stock purchasing. The representation formats include range, numeric, linguistic, colored icon, and arrow icon. The information was updated every 20 seconds. Their results showed there were no main effects of display format.

Visualization of uncertainty has been investigated in many fields. Foody and Atkinson (2002) gave an overview of the most recent studies in modeling the uncertainty in Geographic Information Systems. Botchen, Weiskopt, and Ertl (2005) discussed texture-based visualization of uncertainty in flow fields. Brown (2004) analyzed present visual features used to indicate uncertainty and summarized as follows:

- Intrinsic representation – position, size, brightness, texture, color, orientation and shape
- Further related representations – boundary (thickness, texture and color), blur, transparency and extra dimensionality
- Extrinsic representation – dial, thermometers, arrows, bars, different shapes and complex objects – pie charts, graphs, complex error bars

Many visualization techniques have been applied to these features in uncertainty visualization. Andre and Cutler (1998) used rings to represent uncertainty regarding the location of an entity. Kirschenbaum and Arruda (1994) used an ellipse-shaped representation of the confidence interval of the submarine's location. Finger and Bisantz (2002) investigated using blended and degraded icons. Pang, Wittenbrink, and Lodha (1997) suggested modifying attributes of scene geometry, such as color, shading, reflectivity, and bumpiness, to indicate uncertainty. Wittenbrink, Pang, and Lodha (1996) also investigated using glyphs (graphical forms such as arrows and vertical lines) to display data uncertainty. MacEachren and DiBiase (1991) used the traditional variables in cartography (location, size, value, texture, color, orientation, and shape) along with color saturation to display different types of uncertainty. They also suggested representing uncertainty using pairs of graphics. Animation can also be used (Brown, 2004). The degree of uncertainty corresponds to the degree of motion.

Pang, Wittenbrink, and Lodha (1997) surveyed techniques for presenting data together with uncertainty and focused on scientific visualization. Classifications of methods are reviewed in their paper and a classification, which accounts for different types of uncertainty information or techniques, is proposed. The classification has five characteristics: value, location, data extent, visualization extent, and axes mapping. They present their results for environmental visualization, surface interpolation, global illumination with radiosity, flow visualization, and figure animation. The techniques include adding glyphs, adding geometry, modifying geometry, modifying attributes, animation, sonification, and psycho-visual approaches. A common classification method for scientific visualization is based on data dimension. The algorithms can be categorized into scalar, vector, and tensor algorithms. Unlike scientific visualization, visualization of tactical symbols does not have a natural geometric structure. Most techniques developed for uncertainty visualization in volume rendering are not suitable for tactical symbol display. In this section, we will review the techniques in the following categories: applying simple geometry, modifying geometric attributes, modifying geometry and animation. We then discuss the possible applications to tactical symbol display.

3.1.1. Adding Simple Geometry

In this category, simple graphical shapes (line, arrow, arc, ring, ellipse etc) are used. These shapes are easy to create. They might be suitable for displaying uncertainty in different situations. Glyphs are usually used for vectors in scientific visualization where the data are physically based. For example, Wittenbrink, Pang, and Lodha (1996) used arrows to represent magnitude and direction of winds and ocean currents along with the uncertainties in these dimensions. The general shape of the glyph was a line and arrow; the width of the arrowhead represented uncertainty in heading and multiple arrowheads represented uncertainty in magnitude. In another example, the area of the glyph was used to represent magnitude. Parameters of shapes such as an arc, an ellipse, and a ring might be easily related to the uncertainty. For example, the radius of the circle is used to signal the position uncertainty in investigation of uncertainty display in aviation navigation systems (Andre & Cutler, 1998). Arcs are utilized to display heading uncertainty. The missing segment of a ring represents the uncertainty region. In another example, a study of submarine sonar display by Kirschenbaum and Arruda (1994) provided a graphical display of the area of uncertainty regarding the location of the target. The target icon is surrounded with an uncertainty ellipse. The center of the ellipse is at the target location and the shape gives the range and bearing probability distribution.

3.1.2. Modifying Geometric Attributes

Geometric attributes can be used to represent uncertainty. However, representing uncertainty prevents these graphical dimensions from being utilized for other purpose. Attributes include color, shading, surface normal, lighting, and texture. The simplest approach is to use a color lookup table where a color palette is used to map uncertainty values to different colors. Hengl (2003) discussed using Hue-Saturation-Intensity (HSI) color models in visualization of uncertainty for continuous interpolated and categorical data. Whiteness or paleness is used as a variable to display uncertainty. Color legends are given in two-dimensional legends or color wheels. In two-dimensional legends, hues change on the vertical axis, and saturation and intensity change linearly from low to total whiteness. In color wheels, hues change on the perimeter, and radial distance represents the confusion (whiteness). Then the predictions and prediction error for continuous variables can be visualized by mapping predictions to hues and errors to whiteness. For categorical data, class hues are selected first in the color wheel reflecting the taxonomic similarity of the classes. Then the hues, saturations, and intensities are mapped to Red, Green, and Blue (RGB) values. The color at each pixel is an averaged RGB value of multiple memberships at that point.

Uncertainty values can also be mapped to reflectivity coefficients in shading such as specular and diffuse. Pang, Wittenbrink, and Lodha (1997) showed the different effects of representing uncertainty by altering diffuse coefficients, altering specular coefficients and mapping different values to 2D and 3D textures. Examples of manipulating surface normals can be found in their paper. Hootsmans (2002) compared visualization of uncertainty using different color variables – saturation, intensity and hues. Jiang (1996) investigated some new fuzzy color systems for visualization of uncertainty.

3.1.3. Modifying Geometry

Uncertainty can also be visualized by modifying geometry. Geometry can be transformed, subdivided, or refined. For example, uncertainty can be mapped to the translation or rotation of primitives, or related to how the geometry is warped or distorted. We also include blurred images in this category. Blurring is removal of spatial high frequency details from information which reduces the viewer's ability to recognize fine features (Russ, 1992).

Finger and Bisantz (2002) pointed out that blurring or fuzziness corresponds to a natural way of conveying the uncertainty. They performed experiments, which compared the use of numeric formats to degraded and blended icons for conveying situational estimates. An image can be blurred by using different types of filters.

The visual effect of a Gaussian blur resembles viewing the images through an out-of-focus lens. A normal distribution is used for calculating the transformation to apply to each pixel in the image. Each pixel in the blurred image is an average of the original pixel's value and its neighboring pixels. According to the distribution, neighboring pixels receive smaller weights as their distance to the original pixel increases. The pixelized filter takes a square area and gives it the mean color value of the pixels it contains, while the motion blur filter averages frames.

3.1.4. Animation

Animation parameters such as speed or duration, motion blur, range or extent of motion can be mapped to uncertainty values. Brown (2004) investigated animated visual vibrations as an uncertainty visualization technique. Two values are allowed to exist in the same spatial location. An animation vibrates between the two values to indicate uncertainty. The feature is a function of time, period, floor value, and ceiling value. The oscillation function determines the nature of the transitions. Three functions are used: step, linear, and sinusoidal in Brown's study.

3.2. Dynamic Display Techniques

When updating the information on a tactical map, sudden changes of symbols might cause confusion and unpleasant visual effects. Users might also miss capturing the changing of status. Morphing is an image processing technique used for the metamorphosis from one image to another. The idea is to get a sequence of intermediate images, which represent the change from one image to the other.

Costa, Darsa, Velho, and Wolberg (1995) summarized common morphing techniques in their lecture notes for Special Interest Group on GRAPHics and Interactive Techniques (SIGGRAPH) 95. Cross dissolve is a technique, which has been used by the film industry for decades. The source image and the destination image are superimposed and their color values are blended. The values are continuously changed from 100% of the source image to 100% of the destination image, and a smooth transition is achieved. It is usually used to attain metamorphosis effect between two different objects with similar shapes. Cross-dissolve does not involve geometry alignment. It is not so effective in suggesting the actual metamorphosis. For morphs between faces, the metamorphosis does not look good if the two faces do not have the same shape approximately.

To consider both the shape and attribute, warping between the source and destination images are required. Three specification techniques that have been largely used are specification by partition, specification by features, and automatic specification. Specification by partition is also called specification by meshes. Two meshes, with equivalent combinatorial topologies, are created as part of the geometric data set of the graphical object. Each mesh defines a partition of the object domain. The transformation between two corresponding meshes is specified to attain the desired results. For example, the points on the source mesh will move to the destination mesh, while the neighboring points' movement will be determined by a weighting function, which depends on the relative distance from the point to each mesh point. Radial projection is a strategy of this type. It is often used for transforming star-shaped polygons. The points on the curve are projected to a circle and a linear path is taken to morph to another curve (Pomm & Werlen, 2004). Different than specification by partition which is on the entire domain, feature based specification only distinguishes features. Feature transformations are specified by users. Each feature can be described by a point or a curve. For example, if each feature is described by a line, morphing between two images can be done by first defining corresponding features in the source and destination images, and then mapping between the lines specified. Depending on the intermediate frames required, a set of interpolated lines are obtained. An intermediate frame is obtained by warping the source lines to the intermediate lines, warping the destination lines to the intermediate lines, and then combining the warped images proportionally depending on how close the frame is with respect to the initial and final frames.

The warping specification techniques described above enable the user to specify the transformation only at some finite number of elements belonging to the geometric data set of the graphical object. Automatic specifications are detected by some automatic algorithm. However, despite some attempts, use of the automatic specifications is still rare.

3.3. Impact of Uncertainty Visualization on Decision Making

Prior research has investigated the effects of graphical representation of uncertainty. Kirschenbaum and Arruda (2004) studied the performance effects of graphic and verbal representations of uncertainty within the context of a spatial problem. Their results suggested a graphic/spatial representation of uncertainty may considerably improve the judgments of decision makers. Andre and Cutler (1998) compared a numeric, an arc and a ring representation of uncertainty regarding an object's heading in a simulated anti-aircraft task. The arc representation provided a slight advantage over the other two methods.

Bisantz, Marsiglio, and Much (2005) conducted studies on probabilistic information representation. Participants were asked to generate membership functions corresponding to three uncertainty display formats. They found a high degree of similarity in functions across formats and participants and a strong relationship between the shape of the membership function and the intended meaning of the representation. In another three experiments on simulated stock purchase task, information of stock profitability was probabilistic. Their results showed few performance differences attributable to display formats (blurred and colored icons, linguistic phrases, numeric expressions, and combinations).

In similar studies on utilizing graphical formats to convey uncertainty, Finger and Bisantz (2002) conducted a classification study, which showed that participants could sort, order, and rank icons from five sets intended to present different levels of uncertainty. Then, three icon sets were selected for an experiment in which participants had to identify the status of contacts as either hostile or friendly. Contacts and probabilistic estimates of their identities were depicted on a simulated radar screen in one of three ways: with degraded icons and probabilities, with non-degraded icons and probabilities, and with degraded icons only. Their results showed that participants using displays with only degraded icons performed better on some measures than the other tested conditions.

3.4. Toolkits

McQueary, Krause, Santos, Wang, and Zhao (2004) described the design of the Uncertainty Prediction System (UPSYS), which supports the analysis and visualization of battlefield uncertainty calculation within the context of predictive battlespace awareness. Mewett and Clark (2005) introduced the development of the Intelligence Surveillance and Reconnaissance Dynamic Display (ISRDD). Slocum, Cliburn, Feddema, and Miller (2003) described the development of software that is intended to enable decision makers (and their scientific advisors) to visualize uncertainties associated with the future global water balance. Brown (2004) implemented animated visual vibrations for uncertainty visualization in the Framework for Experimental Visualization in Education and Research (FEVER), which is an extension to OpenSceneGraph. However, no tools have been developed to assist human factors study of uncertainty visualization.

Uncertainty display techniques have been reviewed above in four categories: applying simple geometry, modifying geometric attributes, modifying geometry, and animation. Three techniques are selected from among three categories to implement in the toolkit: 1) Applying simple geometry -- a rectangular bar is added at the top of the symbol to show the probability level; 2) Modifying geometric attributes -- the color is the attribute to be modified, and whiteness (or yellowness) is used as a variable to display uncertainty; 3) Modifying geometry -- blurred images will be used. The three methods are implemented in the toolkit to realize dynamic display: sudden change, cross-dissolve, and feature-based morphing.

4. Software Toolkit Development

A software toolkit was developed to carry out the study. The goal of the toolkit is to provide a tool to display tactical symbols dynamically, to create the designed scenarios and to obtain experimental data. The toolkit is developed in C++ using Qt library. The main window contains a menu bar, a tool bar, two dock widgets, a status bar, and a display area (Figure 4-1). By default, the left dock widget is the scenario setting dialog box, and the right dock widget is the user input dialog box. The toolbar contains two buttons (play and stop) for playing the selected scenario.

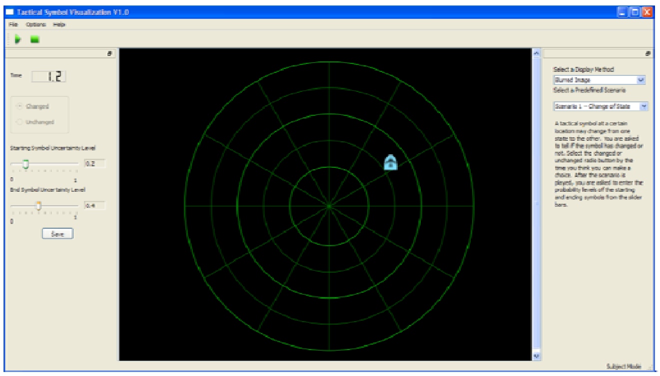


Figure 4-1. Screenshot of the user interface.

The program runs in two modes. Under the experimenter mode, data will not be saved before a new scenario is played. Experimenters can focus on adjusting the scenario parameters, which can be loaded from parameter files. Appendix A contains the user manual of the toolkit. The parameter file format is described in the manual. While under the subject mode, data will be forced to save before a new scenario is played to guarantee collecting all the data in experiments.

4.1. Use Case and Class Diagram

The toolkit is developed using Object-oriented Programming. Figure 4-2 is a use case diagram of the system. It provides the functionalities. Three actors, experimenter, subject, and the toolkit, interact with the system. The explanation of the use cases are given below.

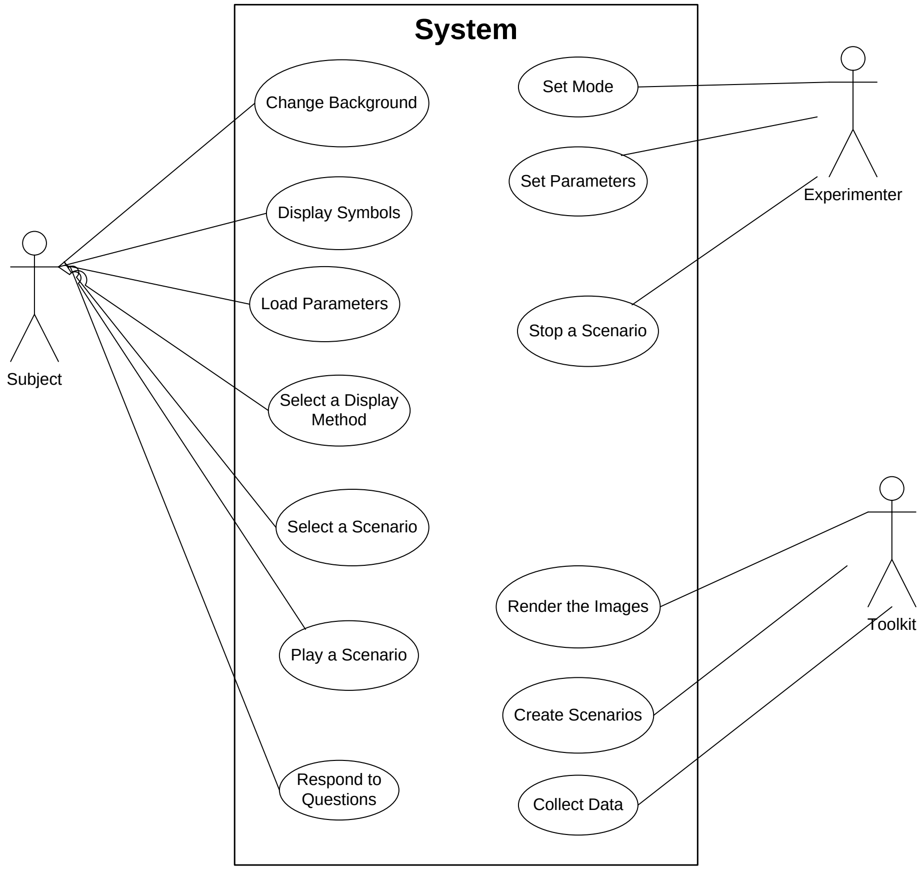


Figure 4-2. Use case diagram of the system.

Change background:

The subject changes the background to simulated radar screen, white background or user defined images. The toolkit updates the background and reloads the symbols.

Set mode:

The experimenter sets the mode to experimenter or subject. In the subject mode the toolkit changes its setting so data are saved before a scenario can be played with the exception for the first time.

Display symbols:

The subject selects display symbols from the help menu. The toolkit displays the techniques used and the symbols (both friendly and hostile) with probability from 0 – 1, in tenths. This is used for training purposes. The current scene will be cleared before displaying these symbols. The displayed symbols will be removed from the scene before a scenario is played.

Play scenario:

The experimenter or subject plays the scenario. If it is running under the subject mode, the toolkit checks whether the data have been saved. If not, it gives an error message and does not play the new scenario.

Stop scenario:

The experimenter stops playing the scenario. If the toolkit runs under the subject mode, the stop button is disabled.

Select scenario

The subject changes the scenario to be played. The toolkit regenerates the scenario.

Select display technique:

The subject changes the display technique. The toolkit regenerates the scenario.

Create scenario:

The toolkit regenerates the scenario once the scenario or display method options have been reset.

Load parameters:

The subject loads parameters from a text file. The toolkit updates the parameters' values.

Respond to questions:

The subject gives feedback based on scenario. For example, when scenario 1 is played, subjects are requested to click the radio button once they detect changes, and recall the start and end probabilities. The toolkit saves these data.

Set parameters:

The experimenter sets parameters in a text file.

Render symbols:

The toolkit renders the dynamic symbols on the screen.

The class diagram of the toolkit is given in Figure 4-3. The main window contains four input widgets and a scenario selection widget. These input widgets take the responsibility to obtain user input. The scenario selection widget is in charge of setting the scenarios and display techniques, and sending signals to the main window to update user interface for different scenarios. The main window also contains a scenario creator. The scenario creator maintains a list of dynamic symbols. The dynamic symbol class takes the responsibility of creating a series of symbols by interpolating the start and end symbols.

4.2. Symbols and Background Images

Symbols can be loaded from Portable Network Graphics format (PNG) formats. Once loaded, the image will be scaled to 33*33 pixels. The class cSymbolImage takes the responsibility of loading images and converting them to pixmaps. The toolkit also provides classes to create primitive shapes such as circle, square, star, and pentagon.

By default, the background image is a simulated radar screen. However, the image formats, including PNG, Joint Photographic Experts Group (JPEG) or Bitmap (BMP) can be loaded as background. It can also be set to white.

4.3. Creating a Dynamic Symbol

Each dynamic symbol contains start and end symbols. It creates a series of images by interpolating these two images. Options of displaying a dynamic symbol include sudden change, cross-dissolve, and feature-based morphing. In sudden change, no interpolation is required. Start images last for a certain period of time and then the end image replaces it. In cross-dissolve, images are superimposed and their color values are blended. The proportion of image A and B changes from 100% of A and 0% of B to 0% of A and 100% of B. Figure 4-4 shows the effect of morphing from a friendly symbol to a hostile symbol. Feature-based morphing is explained in Section 6.

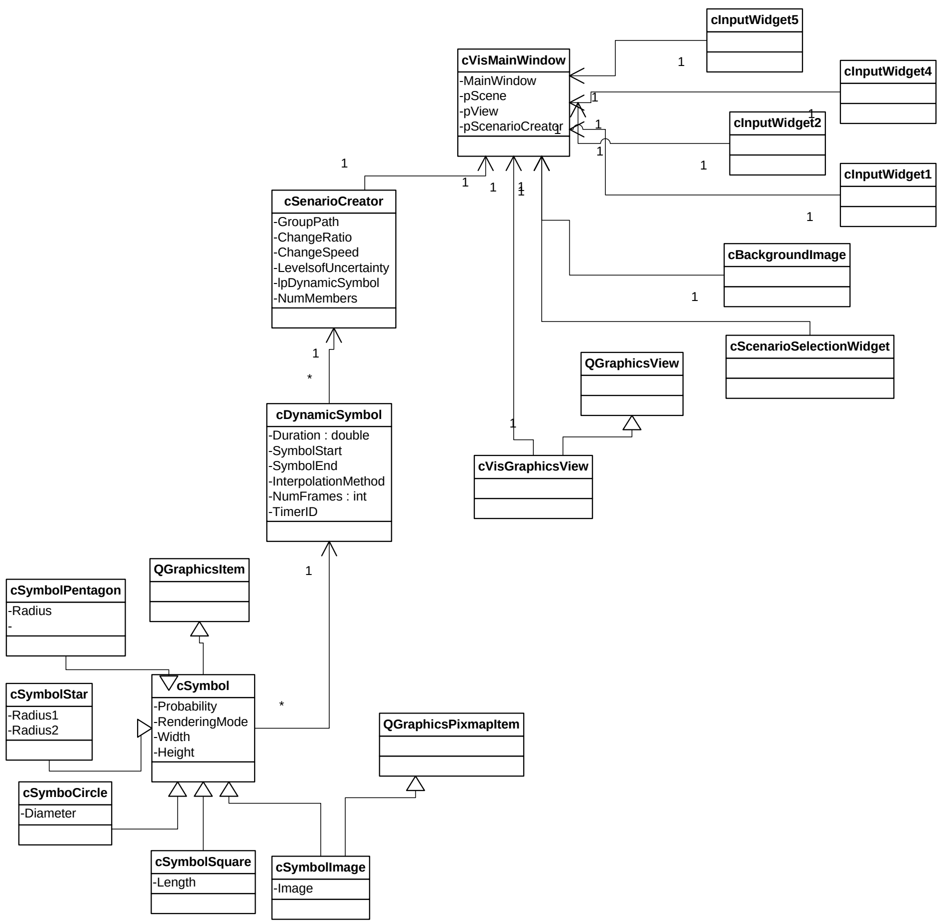


Figure 4-3. Class diagram of the software toolkit.

Figure 4-4. A friendly symbol gradually changes to hostile by cross-dissolve.

4.4. Implementation of Display Techniques

In section 2, uncertainty display techniques are reviewed and three techniques from three categories are selected to be compared. Figure 4-5 shows friendly and hostile symbols displayed in the toolkit with these techniques.

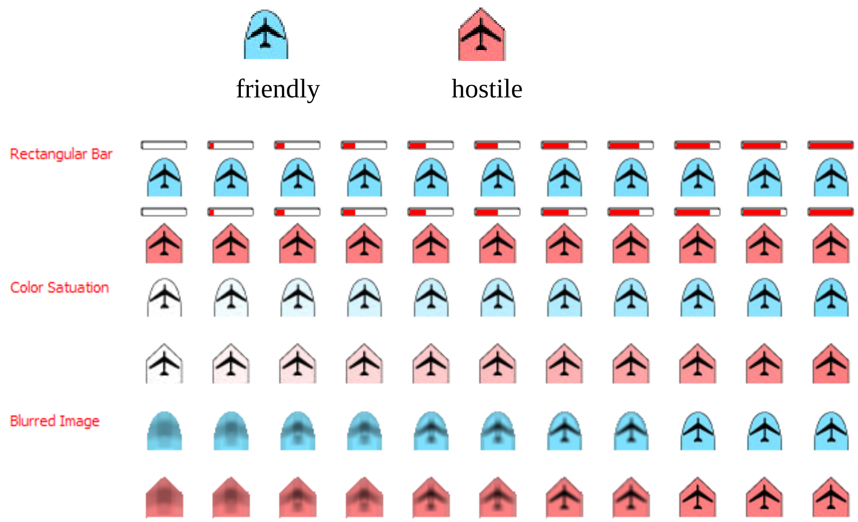


Figure 4-5. Symbols displayed using three techniques.

Rectangular bar technique draws a rectangular bar above the symbol image. The fill of the rectangular bar corresponds to the probability.

Color saturation uses the whiteness of a symbol to display the uncertainty. A color is represented in hue, saturation and, value (HSV). The saturation corresponds to the probability. The saturation of each symbol's fill is set to the product of its original saturation value and the probability. The image is equal to the original when the probability is equal to 1. It has a white fill when the probability is equal to 0.

Blurred image uses a pixelized filter. It takes a square area and gives it the mean color value of the pixels it contains. The transparent neighbors and the neighbors, which are out of boundary, are simply ignored. The length of the square area corresponds to the probability. When the probability equals 1, the length is one pixel, thus the image is the same as the original image. When the probability equals 0, the length is ten pixels. The lengths of the area corresponding to other probabilities are interpolated linearly.

5. Methods

Research on visualization is two-fold, to investigate how to display information, and to study how the information is perceived. An experiment was conducted to compare the three display techniques selected from different categories to understand if there is difference among them on decision-making in dynamic display, and to provide guidelines for selecting uncertainty display techniques in the future.

5.1. Participants

Twenty participants, undergraduate and graduate students from the college of engineering at North Carolina A&T State University, participated in the experiment voluntarily. Eighteen of them finished six visits. The average age was 23 years, with a standard deviation of 6.17. There were four female and 14 male participants. Their computer game playing skills were also evaluated by how many years they had played computer games. Participants were classified as experts if they played computer games for more than five years. Among the 18 subjects who finished all the visits, six of them were novices and 12 were experts.

5.2. Procedure

For the first three visits, the scenarios were organized to sets. Each set contains scenarios 1 to 5. Parameters in each set were different. Participants ran seven sets of scenarios using the three display methods. During the first visit, they were given training and practiced for all scenarios. They were also requested to sort the symbols, which were randomly disordered, with increasing probability so that they were familiar with the mapping of probability. All participants experienced no difficulty sorting the symbols. In the next three visits, participants ran scenarios in sequence. For each scenario, the three display methods were used, and for each display method, participants ran ten randomly set parameters. To avoid confounding of the display methods, participants followed three orders: rectangular bar—color saturation—blurred image, color saturation—blurred image—rectangular bar, blurred image—rectangular bar—color saturation. Each visit took 30-45 minutes.

6. Results

6.1. Scenario 1

In scenario 1, a tactical symbol at a certain location will gradually change from one state to the other; for example, from friendly (with probability *p1*) to hostile (with probability *p2*). Participants set the radio button to indicate when they detect a change. The timer stops when the radio button is clicked, and the time used to detect the change is recorded. After the symbol stopped changing, participants recall the starting and end states level of uncertainty. This scenario is to determine if display formats affect detection of change and perception of uncertainty in a fixed location. In each trial, the location of the symbol and the start and end probabilities vary. The dynamic symbol lasts for five seconds and there are a total of ten frames between the start and end symbols. Three frames of scenario 1 are shown in Figure 6-1.

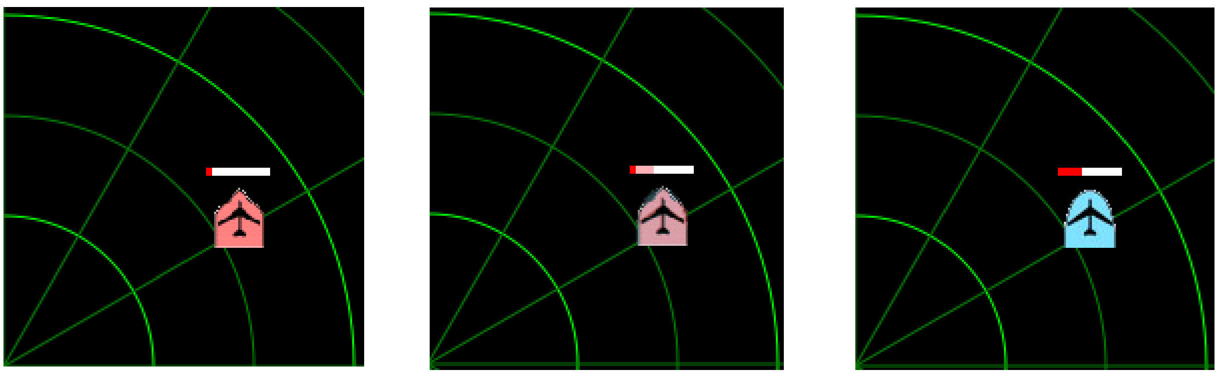


Figure 6-1. Three frames from scenario 1 using the rectangular bar method.

The timeliness and accuracy (the absolute value of user input probability and the defined probability) are analyzed with an Analysis of Variance (ANOVA) (Table 6-1).

Table 6-1. ANOVA of Scenario 1

Dependent Variable: time

Source	Type III Sum of Squares	Df	Mean Square	F	Sig.
Model	6961.075(a)	6	1160.179	228.893	.000
Method	28.826	2	14.413	2.844	.059
skill_level	448.404	1	448.404	88.466	.000
method * skill_level	15.776	2	7.888	1.556	.212
Error	2706.655	534	5.069		
Total	9667.730	540			

a R Squared = .720 (Adjusted R Squared = .717)

Table 6-1 ANOVA of Scenario 1 (Continued)

Dependent Variable: start probability error

Source	Type III Sum of Squares	Df	Mean Square	F	Sig.
Model	27.587(a)	6	4.598	108.050	.000
Method	3.659	2	1.829	42.990	.000
skill_level	.297	1	.297	6.972	.009
method * skill_level	.023	2	.011	.265	.768
Error	22.723	534	.043		
Total	50.310	540			

a R Squared = .548 (Adjusted R Squared = .543)

Dependent Variable: end probability error

Source	Type III Sum of Squares	df	Mean Square	F	Sig.
Model	20.965(a)	6	3.494	75.617	.000
Method	2.257	2	1.128	24.419	.000
skill_level	.645	1	.645	13.966	.000
method * skill_level	.026	2	.013	.278	.757
Error	24.675	534	.046		
Total	45.640	540			

a R Squared = .459 (Adjusted R Squared = .453)

There was a significant effect of display method on accuracy, but no significant effect on detection time. On average, it took about 7 frames (3.45 seconds) for participants to detect the change. For both start and end symbols, the median error of rectangular bar is the smallest (Figure 6-2). For start symbols, the median errors of the color saturation and blurred images are similar, and for end symbols, the median error of color saturation is the greatest. Rectangular bar also gives the smallest means and standard deviations of errors (Table 6-2), while color saturation gives the greatest means. There was significant difference on detection time and probability estimation between novices and experts. The experts performed better with a shorter detection time and higher accuracy.

Table 6-2. Descriptive Statistics for Scenario 1

a) Descriptive statistics of probability estimation errors for the three selected methods

Method		N	Minimum	Maximum	Mean	Std. Deviation
Rectangular bar	Start probability error	180	.00	1.00	.0939	.16785
	End probability error	180	.00	1.00	.1067	.19364
Color saturation	Start probability error	180	.00	1.00	.2983	.22633
	End probability error	180	.00	1.00	.2678	.23270
Blurred image	Start probability error	180	.00	1.00	.2317	.22210
	End probability error	180	.00	1.00	.1722	.22350

b) Descriptive statistics of time (sec) and probability estimation errors for the two skill levels

skill_level		N	Minimum	Maximum	Mean	Std. Deviation
Novice	Time	180	.10	36.60	4.7522	3.36735
	Start probability error	180	.00	1.00	.2411	.24627
	End probability error	180	.00	1.00	.2311	.27141
Expert	Time	360	.00	11.50	2.8192	1.40811
	Start probability error	360	.00	.90	.1914	.20981
	End probability error	360	.00	.90	.1578	.19662

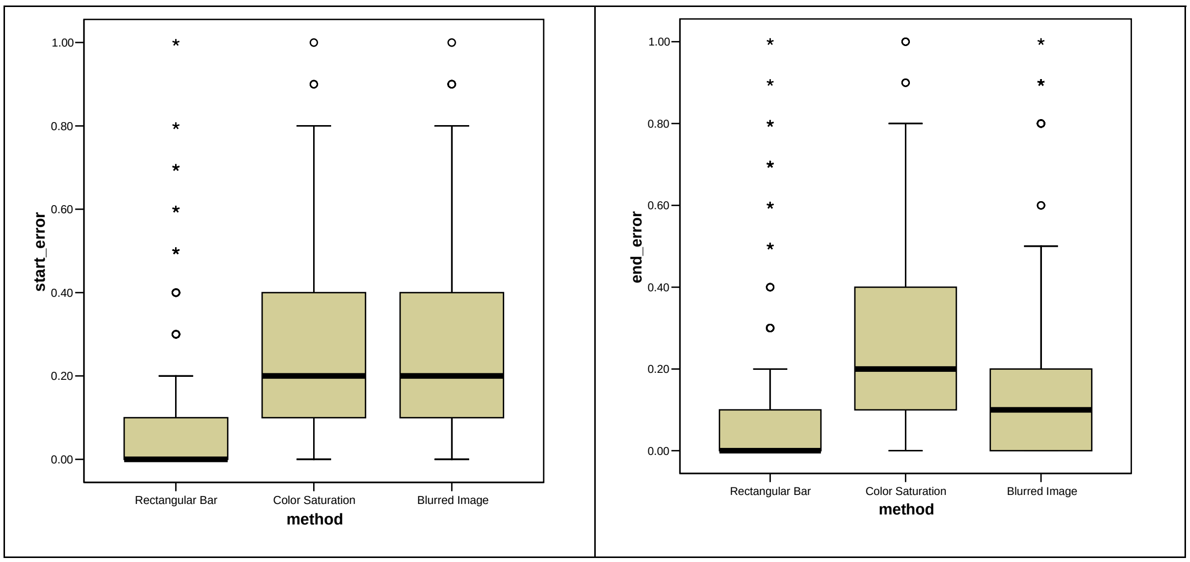


Figure 6-2. Box plots of start and end probability estimation errors of scenario 1.

6.2. Scenario 2

In scenario 2, a tactical symbol moves along a path defined by four points. At each point, the symbol lasts for two seconds and then moves to the next point. The four points are randomly placed on the simulated radar screen with the maximum distance between consecutive points set to 100 pixel length. The state of the symbol does not change, but the probability changes at each location. Participants input their estimation of the travelling path by clicking four points on the screen and probability by using slider bars. This scenario determines if dynamic location of symbols affect understanding of uncertainty. Figure 6-3 displays a user input travelling path.

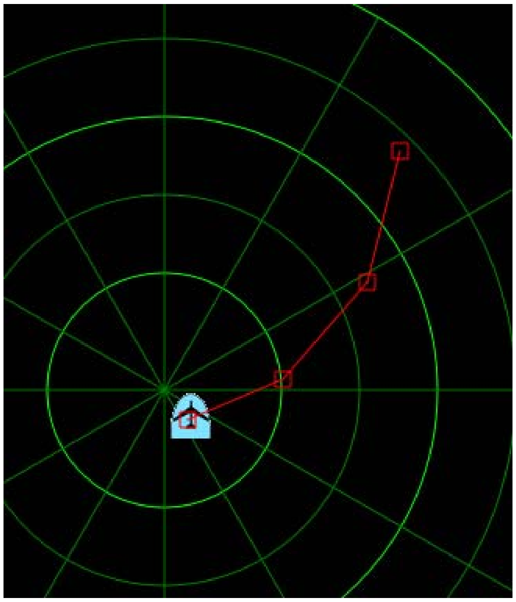


Figure 6-3. Screenshot of a user input travelling path (the symbol is displayed using the color saturation method).

There was a significant effect of display method on uncertainty estimation error (Table 6-3) but no significant effect on location estimation error. All p – values identified as sig. In the tables were greater than .06. The uncertainty estimation error is defined as the absolute value of user input probability and the defined probability, and the location estimation error is the distance between the user-specified location to the defined location. Rectangular bar again gives the smallest mean. The errors of the middle points (2^{nd} and 3^{rd} points) are slightly greater than the first and last points for rectangular bar and color saturation, but this pattern does not show in blurred image (Table 6-4a). Subject's game playing skills do not affect the location estimation errors (all sig. values greater than .08), but playing skills has a significant effect on the uncertainty estimation error for all points, excluding the 2^{nd} point. Overall the experts outperform the novice in uncertainty estimation accuracy (Table 6-4b).

Table 6-3. ANOVA of Scenario 2

Dependent Variable: probability error at point 1

Source	Type III Sum of Squares	Df	Mean Square	F	Sig.
Model	16.857(a)	6	2.809	68.717	.000
Method	1.904	2	.952	23.280	.000
skill_level	.174	1	.174	4.255	.040
method * skill_level	.010	2	.005	.119	.887
Error	16.313	399	.041		
Total	33.170	405			

a R Squared = .508 (Adjusted R Squared = .501)

Table 6-3 ANOVA of Scenario 2 (Continued)

Dependent Variable: probability error at point 2

Source	Type III Sum of Squares	Df	Mean Square	F	Sig.
Model	15.976(a)	6	2.663	65.205	.000
Method	1.366	2	.683	16.724	.000
skill_level	.117	1	.117	2.870	.091
method * skill_level	.006	2	.003	.070	.932
Error	16.294	399	.041		
Total	32.270	405			

a R Squared = .495 (Adjusted R Squared = .487)

Dependent Variable: probability error at point 3

Source	Type III Sum of Squares	Df	Mean Square	F	Sig.
Model	18.569(a)	6	3.095	66.856	.000
Method	.929	2	.465	10.035	.000
skill_level	.235	1	.235	5.079	.025
method * skill_level	.092	2	.046	.996	.370
Error	18.471	399	.046		
Total	37.040	405			

a R Squared = .501 (Adjusted R Squared = .494)

Dependent Variable: probability error at point 4

Source	Type III Sum of Squares	Df	Mean Square	F	Sig.
Model	16.533(a)	6	2.755	64.344	.000
Method	2.515	2	1.257	29.362	.000
skill_level	.603	1	.603	14.074	.000
method * skill_level	.715	2	.357	8.342	.000
Error	17.087	399	.043		
Total	33.620	405			

a R Squared = .492 (Adjusted R Squared = .484)

Table 6-4. Descriptive Statistics for Scenario 2

a) Descriptive statistics of probability estimation errors at four points for the three selected methods

Method	Location	N	Minimum	Maximum	Mean	Std. Deviation
Rectangular bar	point 1	137	.00	.90	.0854	.17044
	point 2	137	.00	.70	.1022	.18128
	point 3	137	.00	1.00	.1358	.20027
	point 4	137	.00	.70	.0701	.12797
Color saturation	point 1	142	.00	.80	.2437	.20122
	point 2	142	.00	.90	.2514	.21495
	point 3	142	.00	1.00	.2521	.23781
	point 4	142	.00	1.00	.2415	.25327
Blurred image	point 1	126	.00	.90	.2397	.23395
	point 2	126	.00	1.00	.2079	.20846
	point 3	126	.00	.90	.2302	.20756
	point 4	126	.00	1.00	.2214	.24020

b) Descriptive statistics probability estimation errors at four points for the two skill levels

skill_level	Location	N	Minimum	Maximum	Mean	Std. Deviation
Novice	Point 1	130	.00	.90	.2254	.23733
	Point 2	130	.00	1.00	.2169	.23332
	Point 3	130	.00	1.00	.2462	.25401
	Point 4	130	.00	1.00	.2431	.28447
Expert	Point 1	275	.00	.90	.1716	.20217
	Point2	275	.00	.90	.1735	.19905
	Point 3	275	.00	.90	.1869	.20247
	Point 4	275	.00	1.00	.1462	.18741

6.3. Scenario 3

In scenario 3, a symbol gradually changes its probability at a location. The symbol is enlarged and then diminished to its original size. The enlarged size is between 1.2 and 1.5 times of its original size, and the whole process lasts for 6 seconds with a total of 21 frames. Participants set the radio button to indicate when they detect a change. The timer stops when the radio button is clicked and the time used to detect the change is recorded. After the symbol stopped changing, participants recalled the start and end probabilities. This scenario determines if display formats affect detection of change and perception of uncertainty in scaling. In each trial, the location of the symbol and the start probabilities, end probabilities, and the enlarged size vary. Cross-dissolve is used to gradually morph from one size to the other.

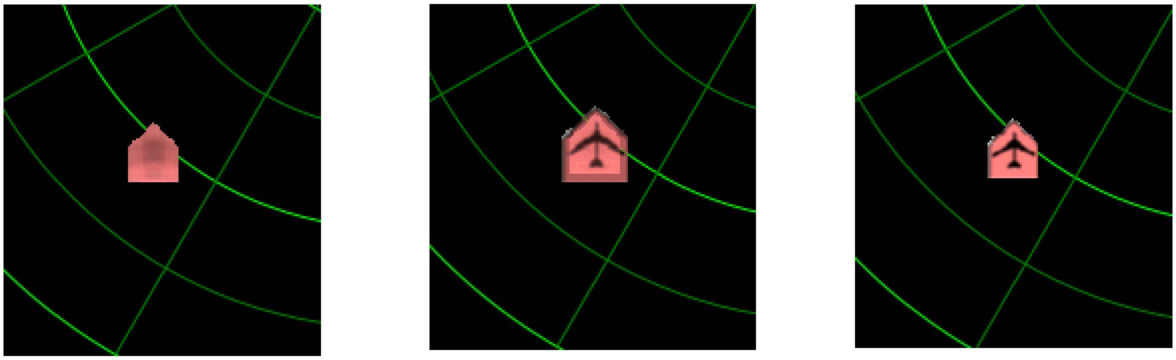


Figure 6-4. Three frames from scenario 3 using the blurred image method.

Table 6-5. ANOVA of Scenario 3

Dependent Variable: time

Source	Type III Sum of Squares	df	Mean Square	F	Sig.
Model	5235.754(a)	6	872.626	268.847	.000
Method	26.305	2	13.152	4.052	.018
skill_level	124.803	1	124.803	38.450	.000
method * skill_level	30.259	2	15.129	4.661	.010
Error	1635.886	504	3.246		
Total	6871.640	510			

a R Squared = .762 (Adjusted R Squared = .759)

Dependent Variable: start probability error

Source	Type III Sum of Squares	df	Mean Square	F	Sig.
Model	18.371(a)	6	3.062	105.705	.000
Method	.790	2	.395	13.632	.000
skill_level	.365	1	.365	12.614	.000
method * skill_level	.178	2	.089	3.077	.047
Error	14.599	504	.029		
Total	32.970	510			

a R Squared = .557 (Adjusted R Squared = .552)

Dependent Variable: end probability error

Source	Type III Sum of Squares	df	Mean Square	F	Sig.
Model	17.518(a)	6	2.920	71.252	.000
Method	.612	2	.306	7.470	.001
skill_level	.222	1	.222	5.425	.020
method * skill_level	.236	2	.118	2.883	.057
Error	20.652	504	.041		
Total	38.170	510			

a R Squared = .459 (Adjusted R Squared = .453)

There was a significant effect of display method on accuracy and detection time (Table 6-5). Rectangular bar has the shortest detection time. For both start and end symbols, the median and mean errors of rectangular bar are also the smallest (Table 6-6). The mean errors of color saturation and blurred image are very close for start symbols. The distributions of errors for start and end symbols are also very similar to those of scenario 1: for start symbols, the medians are close for color saturation and blurred image; for end symbols, color saturation's median is higher (Figure 6-5). Skill levels affect both the detection time and accuracy, and experts outperform novices. The difference on detection time and start probability was statistically significant.

Table 6-6. Descriptive Statistics for Scenario 3

a) Descriptive statistics of time (sec) and probability estimation errors for the three selected methods

Method		N	Minimum	Maximum	Mean	Std. Deviation
Rectangular bar	Time	170	.60	11.90	2.9288	1.61566
	Start probability error	170	.00	.90	.1147	.17258
	End probability error	170	.00	1.00	.1176	.20708
Color saturation	Time	170	.40	9.30	3.1165	1.94768
	Start probability error	170	.00	1.00	.2112	.19321
	End probability error	170	.00	1.00	.2118	.20259
Blurred image	Time	170	.40	10.20	3.4053	2.04781
	Start probability error	170	.00	.70	.2171	.14996
	End probability error	170	.00	.90	.2041	.20246

b) Descriptive statistics of time (sec) and probability estimation errors for the two skill levels

skill_level		N	Minimum	Maximum	Mean	Std. Deviation
Novice	Time	180	1.10	9.30	3.8200	1.89083
	Start probability error	180	.00	1.00	.2172	.19486
	End probability error	180	.00	1.00	.2061	.22724
Expert	Time	330	.40	11.90	2.7848	1.78287
	Start probability error	330	.00	.70	.1612	.16634
	End probability error	330	.00	1.00	.1624	.19550

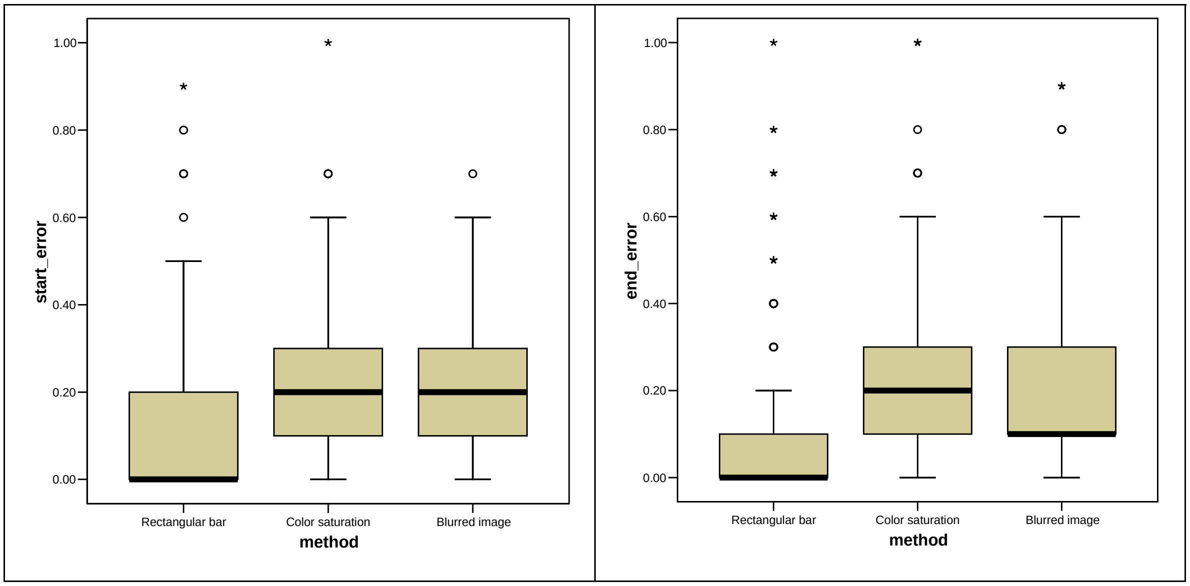


Figure 6-5. Box plots of start and end probability estimation errors of scenario 3.

6.4. Scenario 4

In scenario 4, a symbol's traveling path is linear. It moves at a constant speed. When displayed to subjects, the symbols are placed at a random place around the real location. The distance from the real location is *d*, and its maximum value is 20 pixels, and the probability is given by 1.0- *d*/20. In each trial, a different step size and heading direction is given and the starting point is set at a random location. Participants are asked to guess the next move after observing several moves by clicking the mouse to input a point. We measured the accuracy of their estimations by using the distance between the real location and participant's input. This scenario is to determine if display formats affect decision making in translation. At each point, the symbol lasts for 3 seconds and then moves to the next point. The affiliation of the symbol does not change during the process.

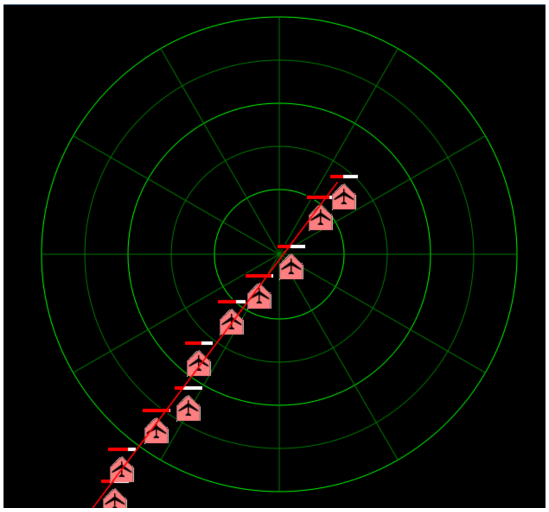


Figure 6-6. Symbols displayed along its travelling path. The line is the real travelling path, which is not shown to participants. Symbols are displayed one at a time.

Table 6-7. ANOVA of Scenario 4

Dependent Variable: time

Source	Type III Sum of Squares	Df	Mean Square	F	Sig.
Model	29835.635(a)	6	4972.606	267.862	.000
Method	49.458	2	24.729	1.332	.265
skill_level	362.336	1	362.336	19.518	.000
method * skill_level	3.594	2	1.797	.097	.908
Error	9727.555	524	18.564		
Total	39563.190	530			

a R Squared = .754 (Adjusted R Squared = .751)

Dependent Variable: location error

Source	Type III Sum of Squares	df	Mean Square	F	Sig.
Model	1442467.456(a)	6	240411.243	88.871	.000
Method	2764.125	2	1382.063	.511	.600
skill_level	7933.482	1	7933.482	2.933	.087
group * skill_level	25199.750	2	12599.875	4.658	.010
Error	1255195.945	464	2705.164		
Total	2697663.401	470			

a R Squared = .535 (Adjusted R Squared = .529)

Table 6-8. Descriptive Statistics for Scenario 4

a) Descriptive statistics of time (sec) and location estimation errors for three selected methods

Method		N	Minimum	Maximum	Mean	Std. Deviation
Rectangular bar	Time	180	.90	21.30	7.0444	3.69900
	Location error	159	7.62	271.28	55.3927	35.57351
Color saturation	Time	170	.90	24.00	7.8153	4.87199
	Location error	154	2.00	367.02	54.7378	61.47173
Blurred image	Time	180	.40	24.40	7.5106	4.50530
	Location error	157	3.61	473.37	54.1170	57.20416

b) Descriptive statistics time (sec) and location estimation errors for the two skill levels

skill_level		N	Minimum	Maximum	Mean	Std. Deviation
Novice	Time	180	.40	18.80	6.3033	4.15234
	Location error	150	3.61	473.37	60.8410	69.85899
Expert	Time	350	1.30	24.40	8.0397	4.38223
	Location error	320	2.00	294.29	51.8977	41.65003

There was no significant difference of time and estimation error among the three methods (Table 6-7). However, we notice the different performance between novices and experts (Table 6-8). Novices tended to make decisions earlier, while experts would wait for a longer time and make decisions based on more accurate information. The maximum distance to the real location (associated with probability 0) is small compare to the symbol size (33x33 pixels). The step size is in the range of 50-100 pixels. Further research will investigate if changing the maximum distance will give more insight and if these methods are adequate for displaying heading uncertainty.

6.5. Scenario 5

In scenario 5, six symbols, which represent the target group, undergo a movement toward the observer. When the target is far away from the observer, the probability of getting accurate information is low. As the target moves toward the observer, the information collected is more accurate. The probability is a function of the distance. $P = 1.0 - dist / MaxDistance$, where *dist* is the current distance between the target and the observer, and *MaxDistance* is the distance at which we assume the probability equals 0. The target group can be friendly or hostile. A symbol will be set by the probability. Assume that the target is friendly. A random number *r* (between 0 and 1) will be generated for each symbol. If $r > P$, the symbol is set as hostile; otherwise it will be set to friendly. (*x*,*y*) is the location of the group. Symbols are located randomly in a circular area centered at (*x*,*y*) with *Radius*. The *MaxDistance* and *Radius* can be set in the parameter file. Figure 6-7 provides two screenshots of the symbols. On the left figure, the target is away from the observer, while on the right figure, it is close to the observer. Cross-dissolve is used for changing state from one to the other. This scenario is to determine if display formats improve change detection of multiple moving target symbols. Participants determine whether the target is friendly.

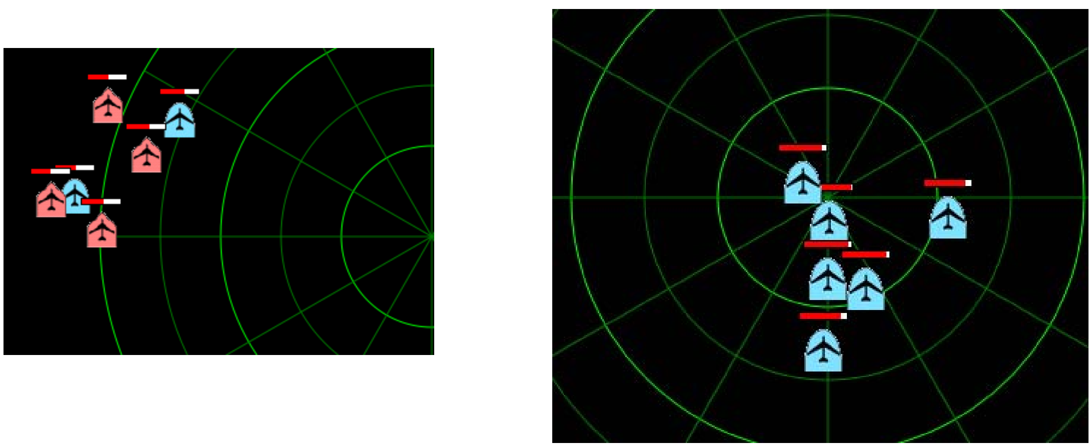


Figure 6-7. Two frames from scenario 5 using the rectangular bar method (Left: the target is away from the observing point, right: the target is close to the observing point).

The time used for participants to make decisions and their choice (friendly or hostile) were recorded. The average probability of the six symbols at the time participants made choices is also analyzed using ANOVA (Table 6-9). There were no significant differences on the time. Color saturation has a smaller mean and standard deviation and outperforms rectangular bar and blurred image in accuracy. The average probability of color saturation is the highest (Table 6-10). This might be the reason that participants made more accurate choices when using color saturation (Figure 6-8). The difference on time and average probabilities of novices and experts was not statistically significant. However, experts made correct decisions at a higher percentage. Experts were correct 60% of the time, while novices were correct 51% of the time (Figure 6-8).

Table 6-9. ANOVA of Scenario 5

Dependent Variable: time

Source	Type III Sum of Squares	df	Mean Square	F	Sig.
Model	58582.153(a)	6	9763.692	312.563	.000
Method	34.424	2	17.212	.551	.577
skill_level	7.569	1	7.569	.242	.623
method * skill_level	.440	2	.220	.007	.993
Error	14806.567	474	31.237		
Total	73388.720	480			

a R Squared = .798 (Adjusted R Squared = .796)

Dependent Variable: average probability

Source	Type III Sum of Squares	df	Mean Square	F	Sig.
Model	184.642(a)	6	30.774	2214.796	.000
Method	.609	2	.305	21.923	.000
skill_level	.000	1	.000	.003	.959
method * skill_level	.016	2	.008	.567	.568
Error	6.586	474	.014		
Total	191.228	480			

a R Squared = .966 (Adjusted R Squared = .965)

Table 6-10. Descriptive Statistics for Scenario 5

a) Descriptive statistics of time (sec) and average probability of the six symbols at the time the decision was made for three selected methods

Method		N	Minimum	Maximum	Mean	Std. Deviation
Rectangular bar	Avg. probability	160	.26	.91	.5798	.12606
	Time	160	1.10	24.30	11.4150	5.46016
Color saturation	Avg. probability	160	.46	.92	.6770	.08509
	Time	160	1.30	23.00	10.6694	4.99556
Blurred image	Avg. probability	160	.27	.87	.5995	.13561
	Time	160	1.20	30.80	11.0431	6.19713

b) Descriptive statistics of time (sec) and average probability of the six symbols at the time the decision was made for the two skill levels

skill_level		N	Minimum	Maximum	Mean	Std. Deviation
novice	Time	120	1.30	30.80	11.2600	6.04310
	Avg. Probability	120	.27	.91	.6193	.13061
expert	Time	360	1.10	27.00	10.9700	5.40961
	Avg. probability	360	.26	.92	.6186	.12283

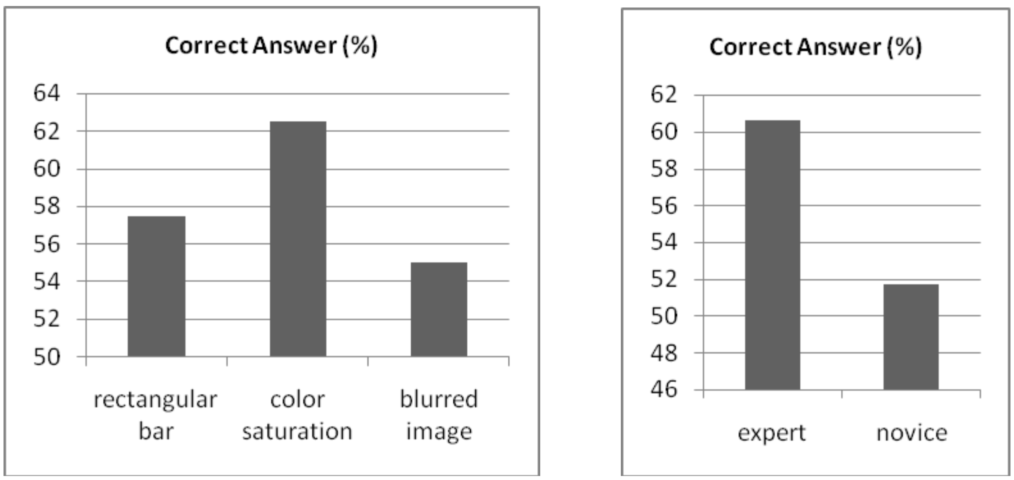


Figure 6-8. Frequency plots of the correct answers in scenario 5.

6.6. Workload

NASA-TLX (Task Load Index) was used to rate the workload. Subjects rated the workload after running a set of scenarios using one display technique. Within-subject ANOVA shows that there were no significant differences of any of the six factors and the overall workload among the three techniques (Table 5-11). Subjects experienced high mental demand and temporal demand, and low physical demand (Table 5-12).

Table 6-11. ANOVA of Workload

		Sum of Squares	Df	Mean Square	F	Sig.
Mental Demand	Between Groups	17.593	2	8.796	.018	.982
	Within Groups	24597.222	51	482.298		
	Total	24614.815	53			
Physical Demand	Between Groups	.926	2	.463	.002	.998
	Within Groups	11852.778	51	232.407		
	Total	11853.704	53			
Temporal Demand	Between Groups	139.815	2	69.907	.129	.879
	Within Groups	27684.722	51	542.838		
	Total	27824.537	53			
Performance	Between Groups	719.444	2	359.722	.692	.505
	Within Groups	26513.889	51	519.880		
	Total	27233.333	53			
Effort	Between Groups	369.444	2	184.722	.519	.598
	Within Groups	18163.889	51	356.155		
	Total	18533.333	53			
Frustration	Between Groups	811.111	2	405.556	.929	.401
	Within Groups	22259.722	51	436.465		
	Total	23070.833	53			
Total Workload	Between Groups	159.371	2	79.686	.300	.742
	Within Groups	13563.834	51	265.958		
	Total	13723.205	53			

Table 6-12. Descriptive Statistics for Workload

	N	Minimum	Maximum	Mean	Std. Deviation
Mental Demand	54	10	100	61.85	21.551
Physical Demand	54	5	75	19.07	14.955
Temporal Demand	54	10	90	50.09	22.913
Performance	54	5	85	45.56	22.668
Effort	54	10	90	59.44	18.700
Frustration	54	5	90	36.94	20.864
Total Workload	54	9.6667	86.0000	53.796292	16.0912524

7. Discussions

The three selected uncertainty display methods' effects on performance vary in different context. In a single symbol displayed in a fixed location with changing state (scenario 1), rectangular bar gives the best results on accuracy. While in multiple moving symbol display (scenario 5), color saturation gives the most accurate results. This indicates that the impact of uncertainty display methods is task-related. Previous research by Kirschebaum and Arruda (1994) and Bisantz et al. (2005) on graphical and other representations of uncertainty also showed task-related results. Kirschenbaum studied graphical and linguistic representations for spatial uncertainty and found some differences between them, while Bisantz *et. al.*'s study for graphical and linguistic representations for state uncertainty showed no differences.

Both scenario 1 and scenario 3 display one symbol at a time. The symbol location is fixed. Their results showed some similarity. In both scenarios, rectangular bar gave the best results. The box plots of start and end probability estimation errors display a similar pattern.

The findings of the study support the hypothesis that display methods affect understanding uncertainty and decision-making performance in dynamic display. In fixed location problems (scenarios 1 and 3), the results indicate that there is significant difference on uncertainty estimation accuracy related to the selected display methods, and rectangular bar gives the best results. In translation problems (scenarios 2 and 4), display methods affect the perception of the uncertainty levels, but not the location information. In a problem with multiple symbols whose location and state change continuously (scenario 5), color saturation gives the best results. The difference of workload of the three methods is not significant.

In all scenarios, experts outperform novices. Thus it indicates that understanding the dynamically displayed symbols can be improved by training and practice. On the other hand, it shows that none of the three selected display methods is self-explained, and their association to the uncertainty is not intuitive.

Further study needs to investigate the relation between display formats and other parameters of dynamic display, such as number of frames and time interval. Future research directions include extending the comparison study for more complex context and realistic battlefield simulation, and exploring methods which are self-explained and intuitive.

8. Feature-based Morphing: A Potential Uncertainty Display Method

Using shapes to represent uncertainty is a potential method. If two symbols correspond to probability 0 and 1, a series of shapes morphing from one to the other can be used to represent probability between 0 and 1. To define the metamorphosis, sets of correspondence of the two images needs to be specified. Commonly used ways include parametric, partition-based and feature-based specifications. These specifications require great user interaction. An automatic specification will allow fast creation of morphing images. In this chapter, we provide a morphing algorithm based on automatic feature-based specification. Assumptions have been made that the symbols are digitized polygons with width of one pixel. However, the algorithm can be extended for more complex geometry in the future.

8.1. Feature-based Morphing

Morphing is a continuous transition from one graphical object to the other. The process contains specification and computation. Specification is an expression of the desired results and computation is a way to obtain the specified goals (Berton, Costa, Darsa, Velho, & Wolberg, 1995). Consider two graphical objects $\mathcal{O}_1$ and $\mathcal{O}_2$, with geometric data sets $U_1 = U_1^1 \cup U_2^1 ... U_n^1$ and $U_2 = U_1^2 \cup U_2^2 ... U_n^2$. A specification of a transformation between $\mathcal{O}_1$ and $\mathcal{O}_2$ consists of a set of ordered pairs

$$\mathcal{P} = \{(s_i, d_i); s_i \subset U_i^1, d_i \subset U_i^2\}$$

and a family of transformations.

$$W^i : s_i \subset U_i^1 \to d_i \subset U_i^2$$

The source set S and target set D are defined as follows.

$$S = \{s_i \subseteq U_1 \mid \text{there exists } d_i \subseteq U_2 \text{ such that } (s_i, d_i) \in \mathcal{P}\}$$

$$D = \{d_i \subseteq U_2 \mid \text{there exists } s_i \subseteq U_1 \text{ such that } (s_i, d_i) \in \mathcal{P}\}$$

Different configurations of *S* and *D* result in different specifications. Specification by partition and specification by features have been largely used. Specification by partition is also called specification by meshes. Two meshes are created as part of the geometric data set of the graphical object. Each mesh defines a partition of the object domain. Mapping of the two meshes defines the mapping of the two objects. Specification by features does not specify the transformation for the entire domain, but only distinguished features and their transformations are specified. The specifications are relied on user input.

8.2. Automatic Feature-based Specifications

We present a method to automatically specify corresponding features without user interaction. Primitive geometric shapes are often used in symbols. These shapes, when digitized, can be considered as polygons. For example, a circle can be approximated with an inscribed regular polygon. In many applications, symbols are represented in digital images. If not, they are first converted to bitmap images. The feature lines are the outline of the polygon. To map the feature lines of two images, scan lines starting from the center of the image are drawn to intersect the source and target sets. Assume the feature line width is 1 pixel. The intersection of the scan line and the source and target point sets form an ordered pair in $\mathcal{P}$. In continuous space, an intersection point can always be obtained (Figure 8-1). However, in discrete space, intersection points are not always found (Figure 8-2). To find a map from source to target so that every point in the source and target is defined in $\mathcal{P}$, we allow a small change of the slope of the scan line to find an intersection in the neighbor area.

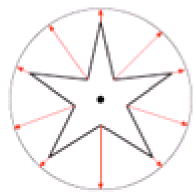
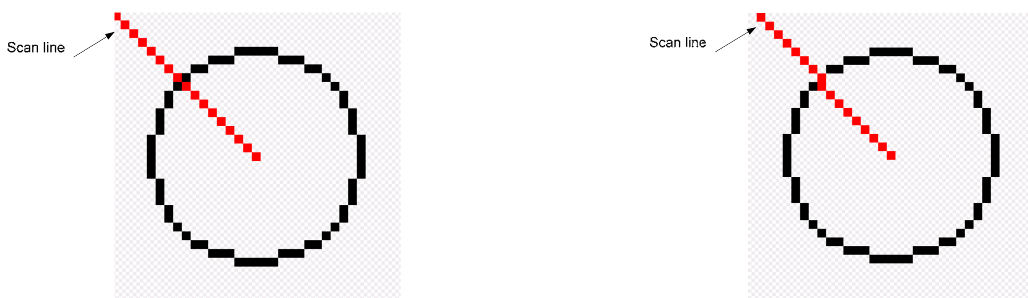


Figure 8-1. Morphing of a star-shaped polygon to a circle (Pomm & Werlen, 2004).



(a) (b)

(a) No intersection found

(b) Intersection found by slightly decreasing the scan line slope

Figure 8-2. Obtaining an intersection of the scan line and a point set.

The pseudo code of creating the ordered pairs of points is given below.

For every point in source point set

Create a scan line starting from the center and pass this point

Compute the slope of the scan line

While (no intersection point is found)

Find the intersection of the scan line with the target set

Increase or decrease the slope of the scan line

Save the pair of point

Remove the target point from the target point set

For every point remained in the target point set

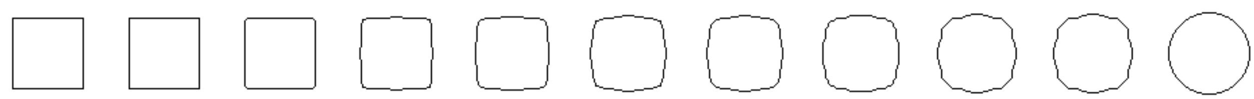
Create a scan line starting from the center and pass this point

Compute the slope of the scan line
While (no intersection point is found)
    Find the intersection of the scan line with the source set
    Increase or decrease the slope of the scan line
Save the pair of point

8.3. Computation

Once the ordered pairs of the source and target point sets are defined, the frames of the morphing sequence are computed by the linear interpolation of the source and target. Examples of morphing from a circle to a square, a circle to a star, and a star to a pentagon are given in Figure 8-3.

(a) A star morphing to a pentagon



(b) A square morphing to a circle

(c) A circle morphing to a star

Figure 8-3. Examples of the automatic feature-based morphing.

8.4. Future Extension

Although we have made the assumptions that the shapes are polygons and the width is one pixel, these assumptions can be easily removed by some modifications of the algorithm. A proposed approach is to find the ordered pairs of points on a scan line according to their radial distances (which is the distance to the center) and to map open curves to open/closed curves by considering radial angles.

9. Conclusions

In this study, previous work on uncertainty visualization has been reviewed. Three display techniques were selected from three categories for the comparison study. Scenarios on a simulated radar display were designed to test subjects' understanding of uncertainty and investigate how the display techniques affect decision making.

A toolkit was developed to display the symbols, create the scenarios and collect experimental data. The toolkit also provides a tool for experimenters to test different scenario settings. It is object-oriented, and extensible. It can be reused in the future for studying a wide range of symbol types, constructing other scenarios and carrying out further comparison study of display techniques.

The experiment containing six visits for each subject was done at North Carolina A&T State Univ. Subjects were recruited from undergraduate and graduate students. Eighteen students finished all visits. Five scenarios of dynamically displayed symbols had been used in the experiment to compare three display techniques: rectangular bar, color saturation and blurred image. The results showed that display methods affect understanding uncertainty and decision-making performance in dynamic display. In fixed location problems (scenarios 1 and 3), the results indicate that there is significant difference on uncertainty estimation accuracy related to the selected display methods, and rectangular bar gives the best results. In translation problems (scenarios 2 and 4), display methods affect the perception of the uncertainty level, but not the location information. In a problem with multiple symbols whose location and state change continuously (scenario 5), color saturation gives the best results. The difference of workload of the three methods is not significant. In all scenarios, experts outperform novices. Thus it indicates that understanding the dynamically displayed symbols using the selected techniques can be improved by training and practice. On the other hand, it shows that none of the three selected display methods are self-explained, and their association to the uncertainty is not intuitive.

Feature-based morphing is a potential method for displaying uncertainty. An automatic feature-based morphing algorithm was developed for polygon shapes with one pixel width. This algorithm can be extended to remove the constraints. The implementation of this algorithm in the toolkit enables exploring this method in the future.

10. References

Andre, A., & Cutler, H. A. (1998). Displaying Uncertainty in Advanced Navigation Systems. *Proc of the Human Factors and Ergonomics Society 42nd Annual Meeting, Santa Monica, CA* , 31-35.

Berton, J., Costa, B., Darsa, L., velho, L., & Wolberg, G. (1995). *Warping and Morphing of Graphical Objects.* Course notes, SIGGRAPH.

Bisantz, A., Kesevadas, T., Scott, P., Lee, D., Basapur, S., Sharma, C., & Roth, E. (2002). *Holistic Battlespace Visualization: Advanced Concepts in Information Visualization and Cognitive Studies.* Buffalo, NY: Center for MultiSource Information Fusioin Lab, School of Engineering and Applied Sciences, SUNY.

Bisantz, A., Marsiglio, S., & Much, J. (2005). Displaying Uncertainty:Investigating the Effects of Display Format and Specificity. *Human Factors , 47* (4), 777-796.

Botchen, R., Weiskopt, D., & Ertl, T. (2005). Texture-Based Visualization of Uncertainty in Flow Fields. *IEEE Visualization '05* (pp. 647-654). IEEE.

Brown, R. (2004). Animated Visual Vibrations as an Uncertainty Visualisation Technique. *the 2nd International Conference on Computer Graphics and Interactive Techniques in Australasia and South East Asia*, (pp. 84-89).

DoD, U. D. (1999). *Common Warfighting Symbology.* Department of Defense Interface Standard MIL-STD-2525B.

Finger, R., & Bisantz, A. (2002). Utilizing Graphical Formats to Convey Uncertainty in a Decition Making Task. *Theoretical Issues in Ergonomics Science , 3* (1), 1-25.

Foody, G. M., & Atkinson, P. (2002). *Uncertinty in Remote Sensing and GIS.* London: Wiley Europe.

Hengl, T. (2003). Visualisation of Uncertainty Using HSI Colour Model: Computations with Colours. *the 7th International Conference on GeoComputation*, (p. 8). Southampton.

Hootsmans, R. (2002). *Fuzzy Sets and Series Analysis for Visual Decision Support in Spatial Data Exploration.* Ph.D. Thesis, Univerity of Utrecht.

Jiang, B. (1996). *Fuzzy Overlay Analysis and Visualization in Geographic Information Systems.* Ph.D. Thesis, University of Utrecht.

Kirschenbaum, S., & Arruda, J. (1994). Effects of Graphic and Verbal Probability Information on Command Decision Making. *Human Factors , 13* (8), 370-390.

MacEachren, A., & DiBiase, D. (1991). Animated Maps of Aggregate Data: Conceptual and Practical Problems. *Cart. & G.I.S. , 18* (4), 221-229.

McQueary, B., Krause, L., Santos, E. J., Wang, H., & Zhao, Q. (2004). Modeling, Analysis and Visualization of Uncertainty in Battlespace. *16th IEEE International Conference on Tools with Artifical Intelligence*, (pp. 782-783). Nov 15-17.

Mewett, D., & Clark, D. (2005). Dynamic Display for Visualising Surveillance Coverage in Complex Terrain. *SimTec*, (pp. 85-89). Sydndy, May 9-12.

OpenSceneGraph. (n.d.). *OpenSceneGraph*. Retrieved 2007, from http://openscenegraph.sourceforge.net

Pang, A., Wittenbrink, C., & Lodha, S. (1997). Approaches to Uncertainty Visualization. *The Visual Computer , 13* (8), 370-390.

Pomm, C., & Werlen, S. (2004). Smooth Morphing of Handwritten Text. *the Working Conference on Advanced Visual Interfaces* (pp. 328-335). Gallipoli, Italy, May 25-28: AVI.

Russ, J. C. (1992). *The Image Processing Handbook.* Boca Raton, U.S.A.: CRC Press.

Slocum, T., Cliburn, D., Feddema, J., & Miller, J. (2003). Evaluating the Usability of a Tool for Visualizing the Uncertainty of the Future Global Water Balance. *Cartography and Geographic Information Science , 30* (4), 299-317.

Spence, R. (2001). *Information Visualization.* Addison-Wesley.

Wittenbrink, C., Pang, A., & Lodha, S. (1996). Glyphs for Visualizing Uncertainty in Vector fields. *IEEE Transactions on Visualization and Computer Graphics , 2* (3), 266-279.

Appendix A: Toolkit User Manual

To run the program, copy the UncertaintyVisV1.0.3 folder to the directory in which you want to place it. Open the subfolder /release and double click on UncertaintyVisV1.0.3.exe. The data are saved in OutputData.txt in the same directory. So please make sure this directory is writable.

1. User Interface

The main window contains a menu bar, a tool bar, two dock widgets, a status bar, and a display area.

The menu bar contains the following items:

File
- Exit

Options
- Mode
- Customize Scenario
  - (Load scenario parameters from a text file,
  - See the experiment plan for the description of scenarios)
- Background
  - Radar Display
  - White Background
  - Background Image (*.jpeg, *.png)

Help
- Display Symbols
- Clear Symbols

By default, the left dock widget is the scenario setting dialog box, and the right dock widget is the user input dialog box. The two dock widgets can be floated or moved to the right or left dock area in the main window. They can not be closed or resized. The widgets in user input dialog box will change when the scenario setting changes.

The toolbar contains two buttons: play and stop for playing the selected scenario.

The status bar shows the mode in which the program is running. It displays either experimenter mode or subject mode.

Keyboard control:

The two groups of radio buttons (Changed and Unchanged for scenarios 1 and 3, Friendly and hostile for scenario 5) have keyboard shortcuts:

Changed: c
Unchanged: u
Friendly: f
Hostile: h

Cursors:

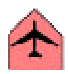
Arrow: used for accessing menu items, input widgets such as combo boxes, spin boxes and sliders

Cross: used for specifying points in the drawing area (in scenario 2 and 4). Once the mouse is clicked, a point location will be marked with a red square. Multiple points are connected by lines.

Symbols:

Friendly and hostile symbols are shown below.

friendly



hostile

2. Running the Program

2.1 Running the program as an experimenter

Experimenters can change parameters for all scenarios by loading a parameter file from the menu Options>Customize Scenario. The file format is described in section 3.

Under the experimenter mode, data will not be forced to save before a new scenario is played.

2.2 Running the program as a subject

Subjects need to run the program following the experimenters' instructions on which type of background and display technique to select and in which order should the scenarios be played. Parameters can be loaded from a parameter file from the menu Options>Customize Scenario.

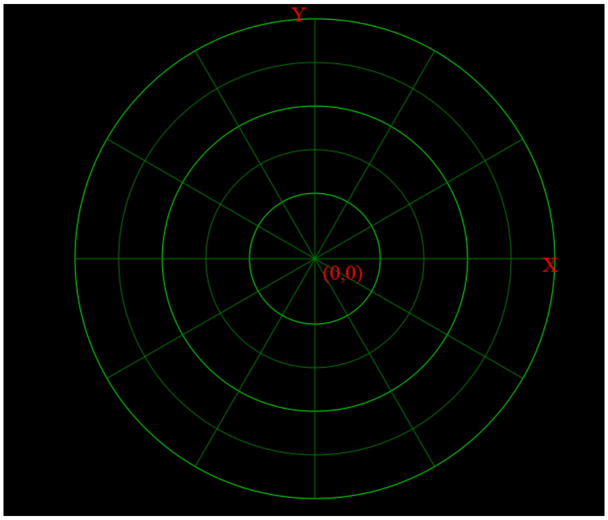
Under the subject mode, data will be forced to save before a new scenario is played. A warning message box will display the information to subjects.

3. Parameter File Format

Loading scenario parameters from a text file provides the convenience for experimenters to explore different parameter settings. A parameter file has an extension *.txt. To load a parameter file, go to the menu item Options>Customize Scenario, and select the file name in the file open dialog box.

The parameters are loaded automatically from "parameters.txt" when the program is initialized.

The origins of the coordinates are in the center of the background. For the radar screen and white background, the width is 800 and the height is 600. The origin of a symbol is at its left upper corner.



A line by line explanation of the file:

Line 1: Scenario1 comments
Line 2: X, Y, StartingProbability, EndProbability, StartingAffiliation, EndAffiliation, Duration, NumFrames
Line 3: Scenario2 comments
Line 4: Duration,NumPoints
Line 5: X, Y, Probability
Line 6:
…
Line (5+NumPoints defined in scenario 2): Scenario3 comments
Line 6+NumPoints: X, Y, StartingSizeFactor, EndSizeFactor, StartingProbability, EndProbability, Duration, NumFrames
Line 7+NumPoints: Scenario4 comments
Line 8+NumPoints: X, Y, DeltaX, DeltaY, Duration, NumSteps
Line 9+NumPoints: Scenario5 comments
Line 10+NumPoints: NumSymbols, Affiliation, Radius, MaxDistance, Duration, NumFrames, NumPoints
Line 11+NumPoints: X, Y
...
Line 11+NumPoints defined in scenario 2 + NumPoints defined in scenario 5

Parameter ranges:
Probability (double): [0, 1.0]
Affiliation (integer) : 0 friendly, 1 hostile
Duration (double):

In scenario 1 & 3, it is the period between a starting symbol and an end symbol >0.0

In scenario 2, 4 & 5, it is the period that a symbol stays at one location.

NumFrames (integer) total number of frames between a starting symbol and an ending symbol >1

SizeFactor (double) : >0 ((0,1) diminished symbol, (1,infinity) enlarged symbol)

NumPoints (integer): >=1

DeltaX(integer): distance in x direction for each step (see the explanation of scenario 4 below)

DeltaY(integer): distance in y direction for each step

NumSteps (integer): >=1

NumSymbols (integer): >=1

Radius (integer): a parameter to control the symbol locations (see the explanation of scenario 5)

MaxDistance (integer): a parameter to control the symbol probability

X and Y: in order to display a symbol in the simulated radar screen or white background, X should be a value in (-400,400), Y should be a value in (-300, 300)

In scenario 4, the symbol's traveling path is a line starting from x and y. It moves DeltaX and DeltaY at each step. When displayed to subjects, the symbols are placed at a random place around the real location. The maximum distance from the real location is 20 (pixels). When it is close to its real location, the probability level is high, and when it is far away from its location, the probability is low. Probability zero corresponds to a distance of 20 pixels and probability one corresponds to a distance of zero. Subjects are asked to guess the next move.

In scenario 5, several symbols, which represent the target group, undergo a fixed movement toward the observer. When the target is far away from the observer, the probability of getting accurate information is low. As the target moves toward the observer, the information collected is more accurate. The probability is a function of the distance. $P = 1.0 - dist / \mathrm{MaxDistance}$, where *dist* is the current distance between the target and the observer, and MaxDistance is the distance at which we assume the probability equals 0. The target group can be friendly or hostile. A symbol will be set by the probability. Assume that the target is hostile. A random number *r* (between 0 and 1) will be generated for each symbol. If $r > P$, the symbol is set as friendly; otherwise it will be set to hostile. (x,y) is the location of the group. Symbols are located randomly in a circular area centered at (x,y). The MaxDistance and Radius can be set in the parameter file. Cross dissolve is used for changing state from one to the other.

4. Output File Format

Subjects' responses to each scenario are saved in "OutputData.txt" in the same directory of the executable. An example of this file is shown below.

Each time a scenario is played, a line describing the scenario name and the display technique is recorded. Each time the save button in the user input dialog box is clicked, the data are saved.

Scenario 1, Rectangular Bar

record:

Time: 3

Choice: changed

starting probability level: 0.5

end probability level: 0.2

Scenario 2, Rectangular Bar
record:
Point: 1
probability: 0.2
xy: 128,177
Point: 2
probability: 0.4
xy: 119,90
Point: 3
probability: 0.6
xy: 79,37
Point: 4
probability: 1
xy: 12,-22

Scenario 3, Rectangular Bar
record:
Time: 1.8
Choice: changed
starting probability level: 0.5
end probability level: 0.9

Scenario 4, Blurred Image
record:
Time: 8.9
XY: -37, -49

Scenario 5, Blurred Image
record:
Time: 21.6
Choice: hostile

---

5. Files Included in this Release

README.doc
README.pdf
Release/
- UncertainVisV1.0.3.exe
- Parameters.txt
- Mingwm10.dll
- QtCore4.dll
- QtCored4.dll

QtGui4.dll
QtGuid4.dll

Images/

AircraftFriendly.png
AircraftHostile.png

Icon/

exit.png
player_play.png
player_stop.png
stop.png

List of Symbols

Graphical objects $\mathcal{O}$

Geometric data set U

Set of ordered pairs $\mathcal{P}$

Family of transformation W

Source set S

Target set D

Point (x, y)